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Experimental Proof-of-Concept of Bidirectional Gigabit Transmission Over Single Step-Index Plastic Optical Fiber

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***Abstract*—We demonstrated a Gigabit bidirectional transmission over a single step-index plastic optical fiber running at 20 m. The solution is attractive for potentially low-cost consumer electronic short-distance cabling at a high data rate requiring simple installation. In particular, thanks to the extremely small cable diameter (2.2 mm overall), it may find applications in brown-field installations that have to reuse existing ducts.**

***Index Terms*—Bidirectional transmission systems, plastic optical fiber (POF) couplers, polymer optical fibers.**

I. Introduction

The use of plastic optical fibers (POFs) in the home networking scenario is taking momentum in the last 3–4 years [1]. Several European operators have launched field-trials of domotic installations using POF (France Telecom, Telefonica, Telecom Italia). The solution that seems most suitable for home-networking is the 1-mm step-index (SI) plastic fibers based on polymethyl-methacrylate (PMMA) material, as standardized by International Electrotechnical Commission (IEC) in category A4a.2 [2]. This letter focuses on this type of fiber, which will be indicated simply as "POF" in the following. The pros and cons of POF with respect to other solutions for home networking have already been reported at length in other papers and will thus be given very briefly here [1].

1) *Compared to glass fibers*: much simpler installation thanks to a much larger core (1 mm for POF versus 50 μm for multimode glass fibers); use of visible light rather than infrared, resulting in higher eye safety and simpler "visual" check of the integrity of the connection; higher mechanical robustness and tolerance to bending. Overall, glass fiber requires skilled technicians for their installation, while POF requires very simple training for the installer, and even a do-it-yourself approach for the final user can be envisioned.
2) *Compared to copper solutions (Unshielded Twisted Pair (UTP) cables)*: possibility to be deployed in power ducts thanks to a complete galvanic and electromagnetic isolation; POF connectorization is even easier than four-pair UTP cables; diameter is smaller: UTP cable is typically 5 mm thick or more, POF can be smaller.

The simplex POF solution thus gives a very good compromise regarding the "diameter issue" (a key point in this letter): the 1-mm POF size is big enough to allow a much simpler connectorization compared to glass fibers, while the overall cable diameter is even smaller than for UTP.

The POF cons are, as of today, a higher cost of the transceiver compared to UTP counterparts, a very small commercial production, and a significant lack in standardization.

Commercially, fast-Ethernet (100 Mb/s) POF transceivers running for some tens of meters are today an established technology used in all the previously mentioned field trials. Best commercial devices available on the market are able to reach approximately 100 m using duplex POF, and approximately 30 m using a single POF. The research inside several European projects (such as ALPHA, POF-ALL, and POF-PLUS) has today demonstrated Gigabit transmission over 40–50 m, a bit rate/distance product that should cover all home-networking requirements even in the long term [3]. Several papers appeared on this topic in last Optical Fiber Communication Conference (OFC/NFOEC) and European Conference on Optical Communication (ECOC) conferences, even in postdeadline papers, demonstrating that 1 Gb/s over POF is possible [4] when using a combination of advanced modulation formats and/or adaptive electrical equalization.

II. Objectives of Our Work

Most POF transceivers proposed up to now (commercially available for 100 Mb/s and in development phase for 1 Gb/s) are based on the use of a duplex cable, i.e., on two POFs inside a cable, one for each transmission direction, resulting in an overall cable cross-section of approximately 4×2 mm (including the protective coating), as shown in Fig. 1. This diameter is already smaller than a typical copper UTP cable, but a further reduction would be beneficial for the most interesting area of application of POF, i.e., in retrofitting existing apartments with a new high-speed internal network, where the cable should be less invasive as possible since, for instance, preexisting power ducts are often used to run the cables. It is thus clear that we should look for the smallest possible cable diameter.

In this letter, we propose and demonstrate a bidirectional transmission over a simplex POF cable at 1.25 Gb/s. We believe that this is the first demonstration of bidirectional transmission

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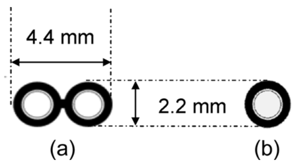

Fig. 1. Cross-section of typical POF cables: (a) duplex and (b) simplex.

over POF at 1000Base-X (Gigabit Ethernet) line rate. From a practical point of view, a simplex POF cable has three important advantages in a domotic scenario when compared to a duplex cable.

1) The cable becomes thinner: a standard duplex cable, as shown in Fig. 1, has a cross section of 2.2 × 4.4 mm, while a simplex cable has a (circular) cross section with a diameter of 2.2 mm, thus becoming significantly smaller than a UTP cable (that in its simplest Cat. 5e version typically has an overall diameter of 5 mm, that increases in higher category cablings).
2) The simplex cable, thanks to its circular cross section, has circular symmetry around its axis and thus it does not have a preferred bending direction, while the duplex cable actually has a preferred bending direction due to its intrinsic mechanical asymmetry. This may turn out to be a key issue for installation in very narrow and crowded power ducts, a common situation in home networking installation.
3) Last but not least, the transceiver would have a single optical port in which the simplex POF should simply be stuck inside, thus not requiring the choice of "which fiber goes where" that happens with a duplex cable.

All these apparently minor issues are actually of paramount importance for brown-field, do-it-yourself installation in existing power ducts, the area where POF may find very important applications. In the rest of this letter, we present the proposed bidirectional experimental system and a detailed characterization of its performance. Bidirectional transmission over single-mode fibers is an established technique today. For instance, in passive optical network (PON), two different wavelengths are used for each direction, and are then separated by a coarse wavelength-division multiplexer (WDM) at the receiver side. The WDM approach for bidirectionality is not easily applicable to POF due to the lack of WDM degree of freedom. In fact, the only reliable sources for Gigabit transmission over POF are red lasers. In our approach, we thus use the same type of lasers (emitting at the same nominal wavelength) for the two transmitters, and we do not need any WDM multiplexer/demultiplexer, but only passive POF splitters.

III. Experimental Setup

We show in Fig. 2 the experimental setup for the bidirectional transmission. We describe here the details for one transmission direction (say from TX1 to RX2), being the opposite direction (from TX2 to RX1) completely symmetric. The modulation was a pure binary ON–OFF. The transmitted data stream was a pseudorandom binary sequence (PRBS) $2^{15} - 1$ pattern sent to an 8B/10B encoder, whose output line rate was fixed to 1.25 Gb/s. A directly modulated red laser diode has been used for the transmitter (UnionOptronics Corp. SLD-650-P10-RG-03,

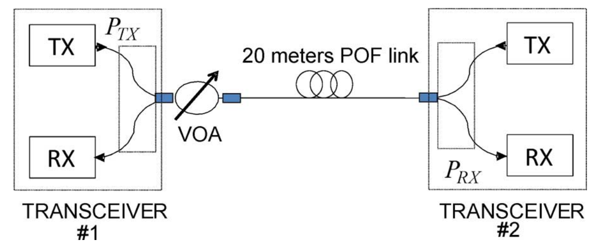

Fig. 2. Experimental setup.

7-dBm peak output power, it is an inexpensive component used for DVD recorders). The laser output is coupled to the POF link by a 1 × 2 POF splitter (from Diemount, attenuation equal to 4.5 dB when used as a coupler, 8 dB as a splitter). The optical power at the output of the transceiver is thus of the order of +2.5 dBm. If this happens to be above some eye-safety limits for consumer electronic devices, practical solutions have already been proposed [6]. On the other side, a second splitter is used to connect to the receiver (we used a commercial device from Graviton, model SPD-2). In the experiment, both lasers were simultaneously active and modulated.

In order to avoid expensive optical components that are not suitable for consumer electronic applications, we did not use any optical isolator or filter at the TX or RX side, and both lasers (nominally) emit at the same wavelength. We measured that the POF splitters used in the experiment have a sufficient isolation between their two input ports (of the order of 40 dB). We also experimentally verified that the optical power that comes from one transmitter and goes into the laser of the opposite transmitter does not damage the laser nor decrease its performance. To this end, we estimate that the minimal attenuation between the two lasers is at least 14.5 dB (12.5 dB coming from the two splitters, and approximately 2 dB coming from the optical connectors).

In our experiment, the two transceivers were connected to a link that included 20 m of POF and a variable optical attenuation (VOA), that was inserted only when needed for sensitivity measurements. At the receiver side, due to the well-know bandwidth limitation of POF at Gigabit rates [3], [4], we used an electronic decision feedback adaptive equalizer (DFE) based on a minimum mean square error (MMSE) adaptation algorithm [5] working in training mode. We used a very common configuration, i.e., a fractionally spaced architecture running at two samples per bit. As already done in many other research works in this area, the algorithm was implemented in off-line processing [5], using a real-time oscilloscope as an analog-to-digital (A/D) converter, then implementing the equalization algorithms in Matlab.

IV. Results

We considered a 20-m POF link, where we added a variable optical attenuator (see Fig. 2) to estimate the available power margin. We evaluated the resulting bit-error ratio (BER) versus the receiver optical power after attenuation, and we show the results in Fig. 3. The star point was obtained by direct error counting at the output of the DFE equalizer, while the dotted values were obtained using a Gaussian approximation for the BER, since error counting was not possible given the limited

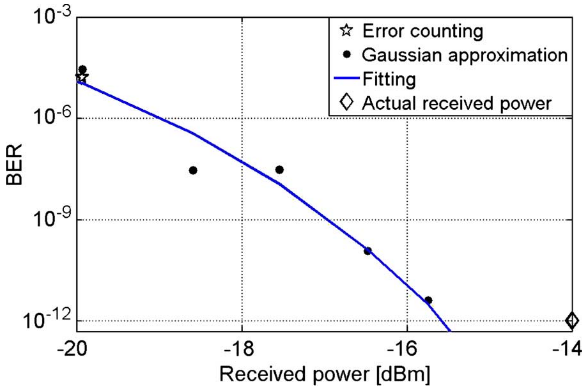

Fig. 3. BER versus received optical power for the 20-m bidirectional link.

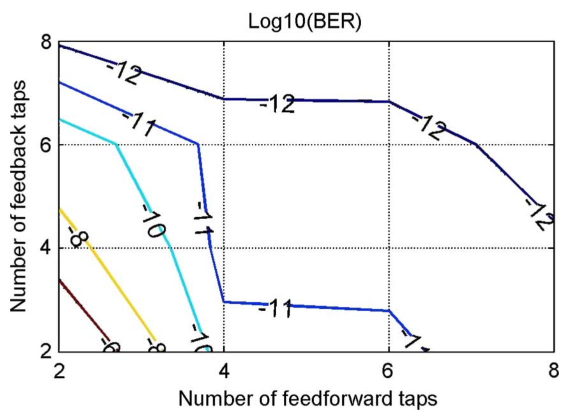

Fig. 4. Contour plots of the BER as a function of the number of feed-forward and feed-back taps used in the adaptive equalizers.

memory of our oscilloscope (corresponding to 125 Kb). In the same graph, we also indicated the received power without the additional VOA, corresponding to -14 dBm. The graph shows that the BER goes below 10^{-12} (i.e., the value required for 1000Base-X) for a received power equal to -15.5 dBm. The actual received optical power in the 20-m-long system, without the VOA, is around -14 dBm, so we conclude that this setup meets the BER $= 10^{-12}$ target set by 1000BaseX specifications without using forward error correction (FEC), with a margin of approximately 1.5 dB.

In order to address the complexity of the required electronic adaptive equalizer at the receiver, we estimate the performance on the 20-m link for the case of received power equal to -14 dBm as a function of the number of taps in the feed-forward and feed-back section of the equalizer. The results are given in Fig. 4, and show that the contour plot corresponding to BER $= 10^{-12}$ requires (as a minimum) eight feed-forward taps and four to five feedback taps, a complexity that appears as very reasonable, being very similar to the equalizer that has been standardized for instance for 10 Gbase-LRM.

V. Comments and Conclusion

We have experimentally demonstrated, for the first time to our knowledge, a fully bidirectional Gigabit/second system over a simplex POF. We obtained a BER lower than 10^{-12} for a 20-m-long system with a system margin of 1.5 dB, using a low-cost red laser at the transmitter. In order to obtain a higher system margin in terms of received optical power, FEC coding can be introduced. If the target before FEC is set at 10^{-4}, we estimated that the required optical power at the receiver for the 20-m system would be below -20 dBm giving a 6-dB margin with respect to the actually received optical power of -14 dBm. We believe this is a very interesting result, demonstrating (for the first time to our knowledge) bidirectional transmission at 1 Gb/s rate over 1-mm SI-POF with large system margin. The results were obtained by off-line processing for the implementation of the equalizer, but the required DSP complexity is not very high, being absolutely comparable to what was proposed in [5]. Moreover, the proposed system is completely "standard" at the TX side, being based on pure binary ON–OFF keying, and requires only the addition of an adaptive equalizer at the receiver. In the following months, we will still work on trying to increase the performance of our systems, in terms of either system margin, avoidance of FEC, or reach. In particular, the current 20-m reach is below what is today considered as the target reach in home networks. We believe that there is anyway a possibility to increase performance by an ad-hoc design of the POF splitters for this specific application, since the ones we used in our experiments have a relatively high excess loss.

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